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FLUID-STRUCTURE INTERACTION ANALYSIS ON HORIZONTAL WIND TURBINE BLADE

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ABSTRACT

The research and advancements in green-energy industries like wind energy system technology has gained an increased interest in twenty-first century due to the reduction of natural resources and thus requires the standardization of the main components of wind turbines to reduce cost. In this study, a coupled analysis of both CFD and static structural for a horizontal axis wind turbine blade is carried out. The blade is allowed to pass through a fluid flow of 12m/s in a computational chamber using Fluent. The pressure thus produced on the blade surface is determined. Further analysis is done by dragging the pressure distribution as an input for structural platform along with a varying rotor speed of 5, 10, 15 and 20 revolutions per minute for finding the Stress and deformation in the blade. The work is carried out for both two and three bladed turbine with change in Tip Speed Ratio and a relative comparison is drawn. Besides, the natural frequencies of the blade are computationally derived and are being validated by refining the mesh.

KEYWORDS: Wind Turbine, Horizontal Wind Turbine Blade, Vertical Wind Turbine Blade & Fluid-Structure Interaction

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Original Article

1. INTRODUCTION

Environmental change is by and large acknowledged just like the best natural test confronting our reality today. Together with the need to guarantee long haul security of vitality supply, it forces a commitment on every one of us to think about methods for diminishing our carbon impression and sourcing a greater amount of our vitality from sustainable assets. Therefore it has led to an increase in research on green-energy industries [1] such as solar and wind energy. The innovative work in wind turbines has made a noteworthy mechanical headway in materials and structures and additionally in assembling forms and got a considerable lift in a few nations. blade being the most essential segment in a wind turbine, it is required to institutionalize the edge to lessen the cost. It is made of composite material [2] with aerodynamic Profile, contorted tip and shifting thickness along its length. Wind vitality frameworks raised on blustery locales are regularly presented to substantial mechanical over-burdens because of extreme climatic conditions and changes in working conditions. The reason of enthusiasm for concentrate the anxiety mapping on a rotor blade is on the grounds that it gives imperative data concerning wind turbine plan and prompt the location of the blade basic Section. Investigation of static and dynamic conduct of a rotor's sharp edge is a fundamental issue in revolving wing and wind turbine [4] blade air flexibility. The geometric

and auxiliary displaying of blade is the initial move towards the entire examination of rotor edge air flexible issues. The fundamental point of the work is the examination of the anxieties coming about because of streamlined powers.

A time of surging development in the Wind energy division has changed the electricity blend in numerous nations and brought critical natural advantage. Wind energy [3] dislodges non-renewable energy source extraction and mining exercises that have conceivably extreme environmental effects. Life cycle carbon dioxide discharges from wind-created power are around 40 times less per kWh than those from flammable gas control and around 80 times not exactly those from coal, decreasing the hazard and effect of atmosphere related dangers to people and biological communities. Many created and creating [8] nations like India have understood the significance of twist as a critical wellspring of energy age. Fundamental measures are being taken up over the globe to tap this vitality for its viable use in control generation. The worldwide breeze vitality insights demonstrate that overall capability of using wind control is apparent. As per Global Wind Energy Council (GWEC), more than 51,477 MW of new wind generating capacity was added in 2014, bringing the global total above 369,553 MW at the end of 2014 as shown in Fig. 1.1.

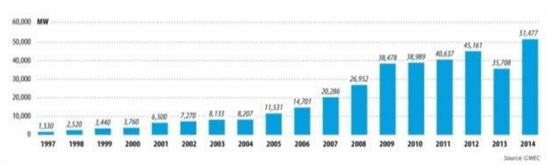


Figure 1.1: Global Annual Installed Wind Capacities 1996-2014

The wind [5] is caused as a result of the absorption of solar energy by the earth surface and in the atmosphere and due to the rotation of earth around its own axis and the sun as well the temperature and pressure difference due the solar flux leads to the generation of wind. The kinetic energy of the turbine blade as a result of the wind flow is converted to electrical power by set of mechanical interface consisting of gear and coupling. The output of the generator is connected to the load (fig. 1.3).

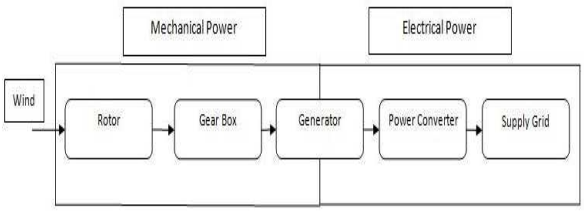


Figure 1.2: Basic Component of a Wind Energy Conversion System

Based on the axis of rotation, [6] they can be separated as horizontal (HAWT) and vertical-axis wind turbine (VAWT). Balakumaran Natarajan and Jaehwan Lee [9] have developed a blade with a single-cell cross-section for a 10 kW wind turbine using CFRP to a large extent. Non-linear static analysis solver 106 was used and the maximum tip deflections are compared Aluminum was considered for the reinforcement of the root section. An advanced beam modeling approach, composed of a two-dimensional cross-sectional analysis and a one-dimensional beam analysis, was used for the structural analysis of the blade. This approach meets the geometrical exactness requirement with less computational effort. The one-dimensional beam analysis and two-dimensional cross-section analysis maintain consistency with three-dimensional elasticity theory while also remaining geometrically exact. Rachid Younsi, Ismail El-Batanony [10] considered the dynamic conduct of a wind turbine with horizontzl axis taking the impacts of the difference in the streamlined stream (in

the unfaltering and insecure cases), the variety of parameters of the artistic development (approach, pitch edge and yaw edge). The coupling of fluid structure has required, on one hand, the parametric displaying, got from the CAD, to assess the aerodynamic forces, and then again, the finite element modeling demonstrating with the hypothesis of 3D bars, to assess the dynamic conduct of the structure. The basic reaction is connected, in an immediate way, to the advancement of the whirlwind as a period work. The flexibility of the CAD and limited components models has permitted an adaptable development between them, on one hand, to assess the new connected powers because of the streamlined stream and, then again, to assess the dynamical reaction of the structure. M. Grujicic, G. Arakere [11] have built up a completely parameterized PC program for mechanized age of the geometrical and limited component fit models of the HAWT-sharp edges. The program empowers the determination of the fundamental sharp edge geometrical and auxiliary parameters (e.g., airfoil shape, size and parallel area of the longitudinal fight/pillar, thickness of the cement layers joining the bar to the outside cutting edge skins, and so on.) and in addition the essential and locally extraordinary composite-cover engineering and lay-up grouping. Genuinely practical, yet bland breeze based (managed and time-changing) stacking conditions are gathered and connected to a cliché 1 MW HAWT-cutting edge with a specific end goal to survey its basic reaction and in addition to evaluate its life span. A basic HAWT-sharp edge material-determination method was created which joins weighted commitments of the material files relating to the cutting edge execution and life span. Jin Chen, Quan Wang [12] has planned the underlying design of a 2 MW composite breeze turbine sharp edge. The new airfoils families are chosen to plan a 2 MW wind turbine edge. The limited component parametric model for the cutting edge is built up. In light of the changed Blade Element Momentum theory, another restricted fluid– structure connection technique is presented. A method consolidating limited component examination and molecule swarm calculation to streamline composite structures of the breeze turbine sharp edge is created. The outcomes demonstrated that, contrasted with the underlying edge, the mass of the streamlined edges is lessened and particularly for the plan II (the area of sharp edge fight top is viewed as one of the factors) which display more mass sparing. C. Kong, J. Blast [13] have outlined,fabricated, tested, an E-glass/epoxy composite blade for a 750 kW medium scale HAWTS and assessed with the proposed configuration stream. The different load cases indicated by the IEC61400-1 global particular and GL Regulations for the breeze vitality change framework were considered, and a particular composite structure design that can successfully persevere through different loads, for example, streamlined and inertial burdens, icing loads, aqueous and mechanical burdens was proposed. The basic examination was performed to assess the proposed plan arrangement utilizing the FEM. A worthy sharp edge auxiliary design was resolved through the parametric investigation. A full-scale static auxiliary test was completed at the recreated streamlined burdens. The exploratory outcomes demonstrated that the outlined blade had structural integrity. Ashwani Kumar, Arpit Dwivedi [14] have arranged a 3D strong model applying SOLIDEDGE programming and is exchanged to ANSYS 14.0. A detail investigation of Al 2024 breeze Turbine cutting edge utilizingstructural and modal analysis examination is done and the structural and vibration issue of the Al 2024 wind turbine blade utilizing FEM strategy was being done. The investigation comes about were checked with exploratory outcome accessible in literature's. H. Hamdi, C. Mrad [15] have displayed investigative and numerical progression investigations of a horizontal axis wind turbine blade subjected to aerodynamic, centrifugal, gravity, and gyroscopic loads. The edge, absorbed to a long light emission cross segment, is made out of homogeneous and isotropic material. It is discretized with blade components of steady areas. Utilizing Finite Element Method (FEM), the gathering of these components constitutes a rough model of the blade. The diagnostic investigation comprises on characterizing the basic frameworks of unbending nature, mass, and gyroscopic coupling amongst vibration and the blade pivot, and also the elementary vector of the external loads. The numerical

examination manages the determination of the straight arrangement of conditions of the blade movement. At that point, it will be conceivable to compute its static and dynamic reactions for a handy case. The numerical outcomes demonstrate that the blade presents cyclic distortions under the thought about loadings. These managed vibrations specifically influence the weariness life of the blade, prompting a noteworthy lessening in the operational effectiveness of the wind turbine.

For current project I have considered the effect of stress developed in the blade surface is a key point while determining the performance and efficiency of the wind turbine. This research work suggests a new computational approach for determining the stress and deformation of a horizontal wind turbine blade. A coupled study of both Computational Fluid Dynamics and structural analysis has been taken in to consideration. The blade was allowed to pass through a fluid flow of rated 12m/s and the pressure so developed in the blade profile has been analyzed. However this pressure is further extracted in the structural platform as an input parameter for determining the stress and deformation in the structure. Besides, the analysis is carried out by changing the rotational speed of the rotor. The speed so taken here are 5, 10, 15 and 20 revolution per minute. Further a change in the number of blades as well as Tip speed ratio gives a comparative study on how they affect the overall stress on the blade surface. Modal analysis has been performed on the blade in order to check the natural frequency of the blade.

Problem Description

From the review on the previous studies, it has been found that the literature on deformation and stress analysis in wind turbine blade due to variation in rotor speed are rarely reported. The initial rotor speed does have an important effect on the performance of the turbine blade. Aim of the study is to have a comparative analysis on that. The key objectives of the work are:

- To study the effect of stress on the blade surface due to variation of rotor speed.
- To study the effect of stress on the blade surface with the variation of no. of blades.
- To study the modal analysis of the turbine blade.

2. METHODOLOGY

Commercial CAD software has been used to model a specified Horizontal wind turbine blade as. The model is then extracted to the ANSYS Workbench. Computational Fluid Dynamics gives the idea about pressure force acting on a component present in a fluid flow. In this work CFD tool of ANSYS i.e., FLUENT has been used to determine the effect of pressure on the blade surface. After finding the pressure and force distribution on the blade surface, it is further operated on the structural field by applying the rotational speed and the CFD output of pressure to find out the stress and deformation in the structure. A comparative study has been done by varying the TSR to check the changes in deformation as well as stress. Further Modal analysis has been carried out and validation has been done by refining the mesh size.

Theoretical Background

The speeds of rotor [17] have a greater impact on the performance of the wind turbine blade. If a rotor slowly rotates, it enables the wind to go unperturbed through the holes of the blade with little power extraction. Similarly if the rotor rotates too fast, it also appear like a solid wall to the wind flow and thus reducing the power extraction. And therefore it is necessary to keep in mind the angular velocity of the rotor to the wind speed to get maximum efficiency while going for designing a wind turbine. Wind turbine must be intended to work at their ideal tip speed proportion so as to separate

however much power as could reasonably be expected from the win stream. The rotor airfoil profile and the no. of cutting edges significantly impact the wind tip ratios

The relationship between the wind speed and the rate of rotation of the rotor is characterized by a non-dimensional factor called as Tip Speed Ratio (TSR). Tip speed ratio is the speed of the rotor tip with respect to the free stream wind speed.

$$\text{TSR: } \lambda = \frac{u}{V} \tag{3.1}$$

The Torque Coefficient (Ct) is also dependent on the TSR and is defined as the ratio between power coefficient (Cp) and tip speed ratio (λ):

$$C_t = \frac{Cp}{\lambda} \tag{3.2}$$

The power coefficient can be defined as the ratio between power extracted by the wind turbine relative to the energy available in the wind stream.

$$C_P = \frac{P_{rotor}}{P_{max}} \tag{3.3}$$

Power of the rotor (Protor) can be expressed as:

$$P_{rotor} = \frac{1}{2}\rho A\left(V_{u_2} - V_{d_2}\right)R\omega \tag{3.4}$$

Power generated from the kinetic energy of the free flowing stream can be expressed as:

$$P_{max} = \frac{1}{2}\rho AV_3 \tag{3.5}$$

Now from Equation (3.4) and (3.5),

$$C_P = (\frac{1}{2}\rho A\left(V_{u_2} - V_{d_2}\right)R\omega)/(\frac{1}{2}\rho AV_3) \tag{3.6}$$

Here ρ is the density of wind, A is the cross-sectional area of the blade, Vu is the upstream wind velocity, Vd is the downstream wind velocity, V is the wind velocity, λ is the tip speed ratio and ω is the angular velocity.

The optimal tip speed ratio will also depends on the number of rotor blades of the turbine. If the smaller the number of blades, the faster the wind turbine has to rotate to remove maximum power from the wind.

In this research work, a comparative study of stress in the turbine blade has been done on varying the rotor speed or in other word varying the tip speed ratio.

3. DESIGN MODEL

In order to determmine the shape of the blade, the program developed by the National Wind Technology Center called WT_Perf. WT_Perf is taken in to consideration. It uses blade element momentum theory in order to approximate blade loading as well as the power output. The technical specification of GE 1.5 XLE wind turbine is used for the design of the blade. The airfoil being used here is NREL (National Renewable Energy Labrotory) S-series (fig.4.1)

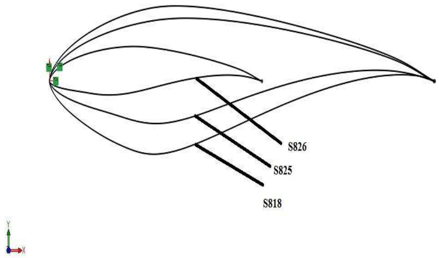
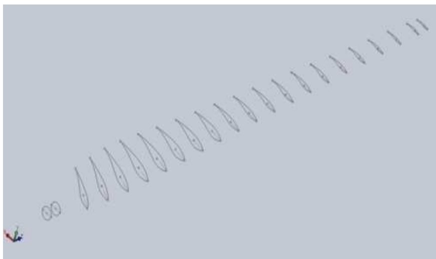


Figure 3.1: NREL S-Series Airfoil S818, S825 and S826

Here 19 blade elements and three airfoils: S818, S825 and S826 are used. Since the programme uses the nondimensional version of blade element momentum theory, it allows to easily scaling the results. The root chord length and the tip cord length is taken to be 1m and 2.5328m respectively. The length of the blade is taken to be 42.25m. There is a twist from root to tip section with 420. The start of the blade is the round center segment. This round root changes into the S818 airfoil, which at that point advances to the S825 airfoil, which at that point advances into the S826 airfoil utilized at the tip. The entire particular of the sharp edge geometry is given.

After defining the full blade geometry, the process of building the blade for the FEA model is done. In order to manage the creation of the blade and to ensure maximum flexibility and computational efficiency within ANSYS, it is being designed in solid works CAD package as a lofted surface. The surface loft command is used to connect these various sketches into a single body, letting Solid Works automatically generate the intermediate blade shape between each defined airfoil. To minimize unnecessary complications in the geometry, each section is lofted using the airfoil leading edge as the loft guide point. The schematic diagram of the turbine blade is shown in Fig. 4.2.



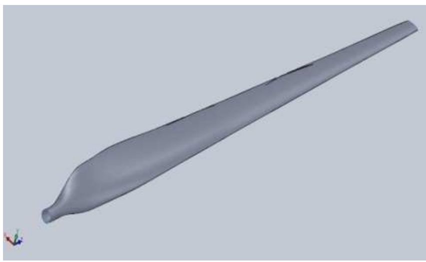


Figure 3.2: (a) Figure 3.2: (b)

Solidworks Model of the Blade Skeleton with Lofted Surface

Computational Mesh Generation and Boundary Condition

Choosing a suitable computational domain is a key step in correctly reproduing fluid-dynamic phenomena. The domain should be an optimized one to take in to account the requirement of correct meshing. Too great domain would lead to an unnecessary increase in the number of cells and hence the computational time. The Computational domain of the blade is consisting of inlet for wind flow over the blade surface, Outlet for the exit of the wind and is maintained sufficient distance from the blade. The fluid domain of the rotor is decided based on the number of blades. The analysis is carried out for both two and three bladed turbine and for which the computational boundary is considered as a part of a sphere with angle of 1800 and 1200 for the two-bladed and three-bladed turbine respectively(fig.4.3).

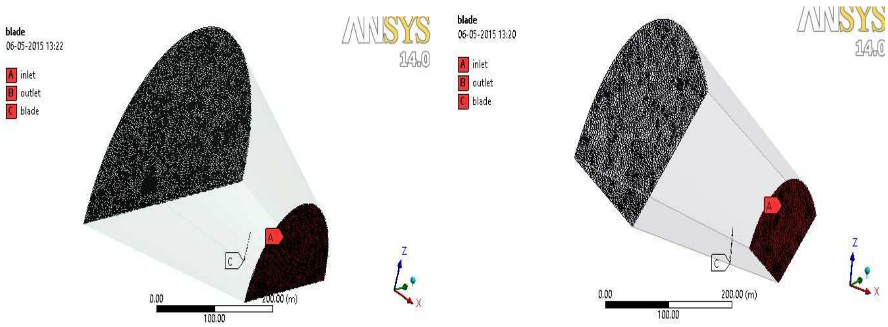


Figure 3.3: (a) Figure 3.3: (b)

Meshed Computational Domain for Two and Three Bladed Turbine

The mesh for the computational cell is composed of tetrahedran cell. Total no. of nodes and no. of cell that have considered for two bladed turbine are 164443 and 904405 and for three-bladed turbine are 47431 and 253001 respectively. The turbine blade is allowed to pass through the air flow. After generating the mesh the boundary conditions (BC) are defined.

- The inlet face of the fluid domain was defined as VELOCITY INLET type BC
- The outlet face of the fluid domain was defined as a OUTFLOW type BC
- A symmetry type boundary condition was used for the lateral surface of the fluid domain.

A numerical analysis has been performed on the blade surface using ANSYS Fluent software. Angle of attack is maintained as 60. The inlet air speed is considered as standard 12 m/s. The solver settings used were as follows:

- Steady state Pressure Based solver with absolute velocity formulation.
- Boundary condition setting on fluid domain as inlet, far field and outlet (velocity inlet, symmetry and pressure outlet respectively).
- First order upwind discretization method for Momentum and turbulence equations.
- Least square Cell Based method for gradient.
- Simple algorithm is applied for the coupling of pressure and velocity.
- Control monitor of the iterative process to check to check convergence.
- Initialization and setting of post processing parameters.

After performing the computational simulation and converging the solution the power coefficient (Cp) and torque coefficient values (Ct) are calculated for input boundary cdition and rotational speed of the turbine. The blade velocity, the flow around the turbine using velocity streamline and the pressure distribution on the blade surface can be visualised thereafter. The dynamic pressure contour near the rotor blade is shown in the figure both for two and three bladed turbine (Fig.4.4).

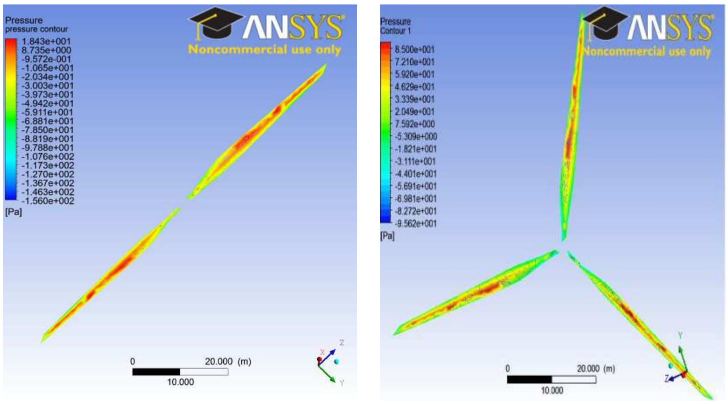


Figure 3.4: (a) Figure 3.4: (b)

Pressure Contour from CFD Analysis

4. STRUCTURAL ANALYSIS AND DISCUSSION

The same turbine model is drag into the structural window for analysis of stress and deformation. Material used for final analysis is E-glass LY556 epoxy resin lamina. The reason behind choosing composites is due to its less mass and high stiffness. The mechanical properties of the material (E-glass LY556 epoxy resin lamina) considered in the analysis are as follows (Table 5.1).

Table 4.1: Material Properties

E-glass LY556 Epoxy Resin Lamina			
Property	**Value**	**Property**	**Value**
Density	2000kg/m3	Poisson's Ratio YZ (vyz)	0.336
Young's Modulus in X dir. (Exx)	34.412 GPa	Poisson's Ratio XZ (vzx)	0.217
Young's Modulus in Y dir. (Eyy)	6.531 GPa	Shear Modulus XY (Gxy)	2.433 GPa
Young's Modulus in Z dir. (Ezz)	6.531 GPa	Shear Modulus YZ (Gyz)	1.698 GPa
Poisson's Ratio XY (vxy)	0.217	Shear Modulus XZ (Gyz)	2.433 GPa

Mesh Generation

A proper meshing is has been applied to the blade surface with refinement as it may affect the analysis in greater way. Computational mesh for the blade surface consists of traingular surface mesh with no. of nodes and no. of cells are 3343 and 6672 respectively. Fig. 5.1 represents the complete meshed structure of the blade profile.

Figure 4.1: Meshed Model of Wind Turbine Blade

After applying proper meshing to the blade surface, structural load is applied to it. The pressure distribution of CFD output is considered here as the load due to air flow. The Fluid-Structure interaction is shown in the Fig. 5.3.

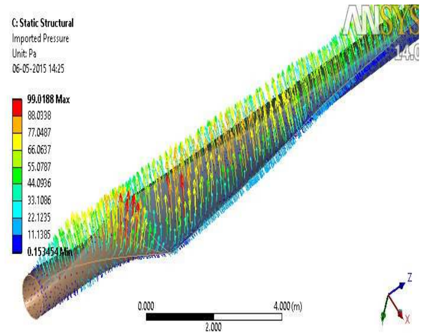


Figure 4.2: Wind Pressure Distribution on the Blade Surface

Besides, an initial rotational speed of 2.22 revolutions per second is applied along the axis of the turbine.

5. RESULTS AND ANALYSIS

During the analysis a number of experiments have been performed by changing the rotor speed or in other word by changing the Tip Speed Ratio. Further the experiment was carried out for both two-bladed as well as three bladed turbines. The figure below shows the results of stress and deformation with the respective TSR and blade numbers.

Equivalent Stress

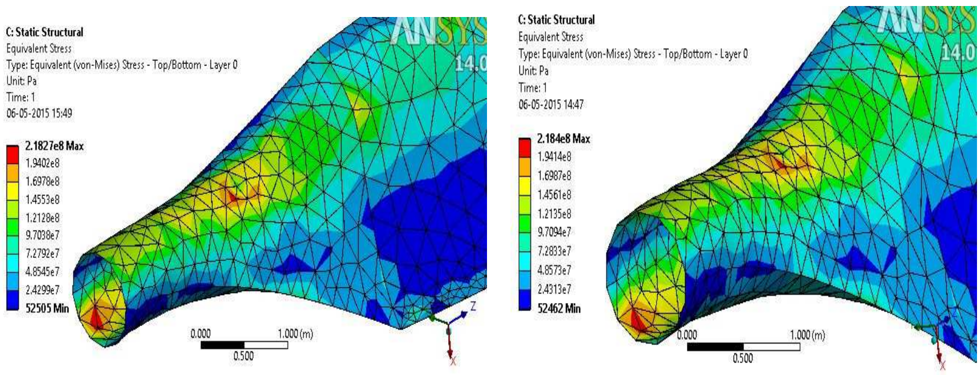


Figure 5.1: Equivalent Stress at TSR 1.85 and 3.70 (2-BLADED)

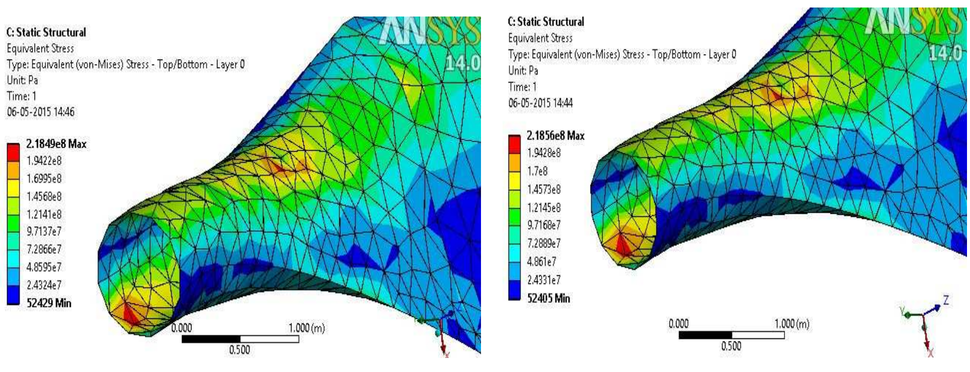


Figure 5.2: Equivalent Stress at TSR 5.56 and 7.41 (2-BLADED)

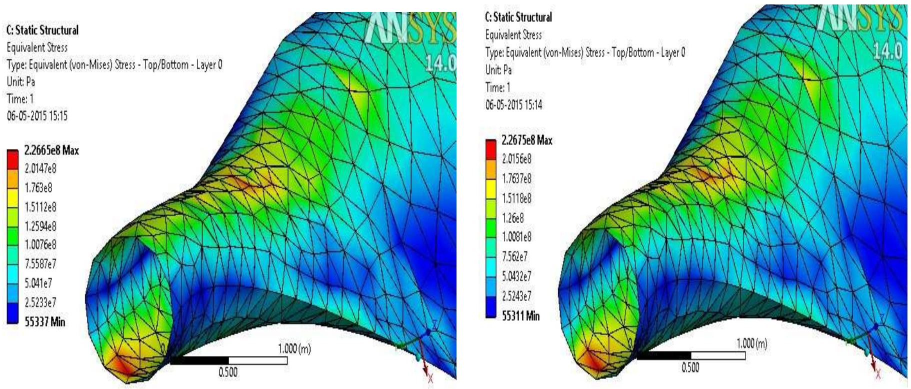


Figure 5.3: Equivalent Stress at TSR 1.85 and 3.70 (3-BLADED)

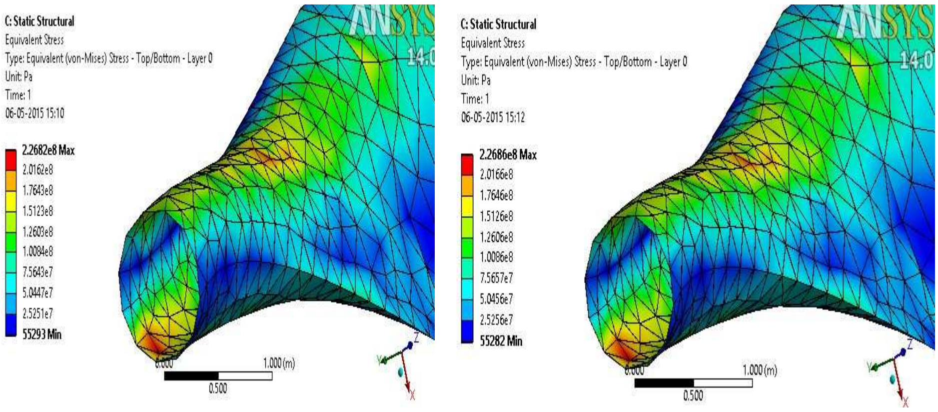


Figure 5.4: Equivalent Stress at TSR 5.56 and 7.41 (3-BLADED)

The details of the stress distribution on the blade surface are illustrated below.

Table 5.1: **Details of Equivalent Stress**

Equivalent Stress (Gpa)			
For Two Bladed Turbine		For Three Bladed Turbine	
TSR: 1.85	0.21827	TSR: 1.85	0.22665
TSR:3.70	0.2184	TSR:3.70	0.22675
TSR:5.56	0.21849	TSR:5.56	0.22682
TSR:7.41	0.21856	TSR:7.41	0.22686

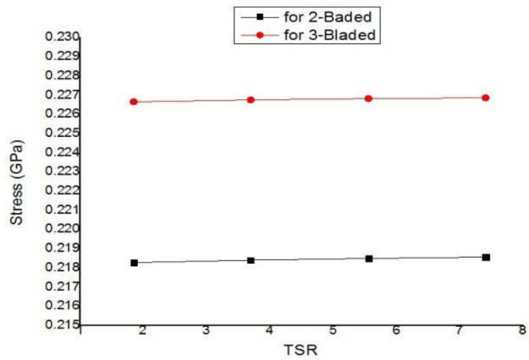


Figure 5.5: Comparison Curve of TSR Vs Stress

5.5.1: Equivalent Strain

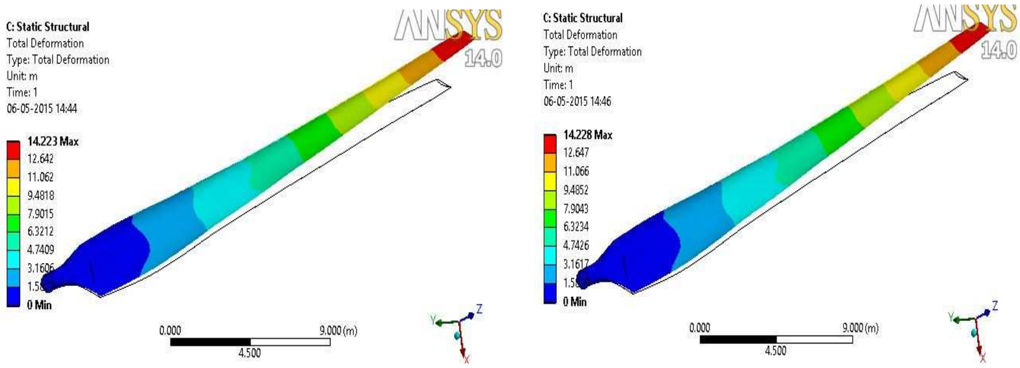


Figure 5.6: Deformation at TSR 1.85 and 3.70 (2-Blade)

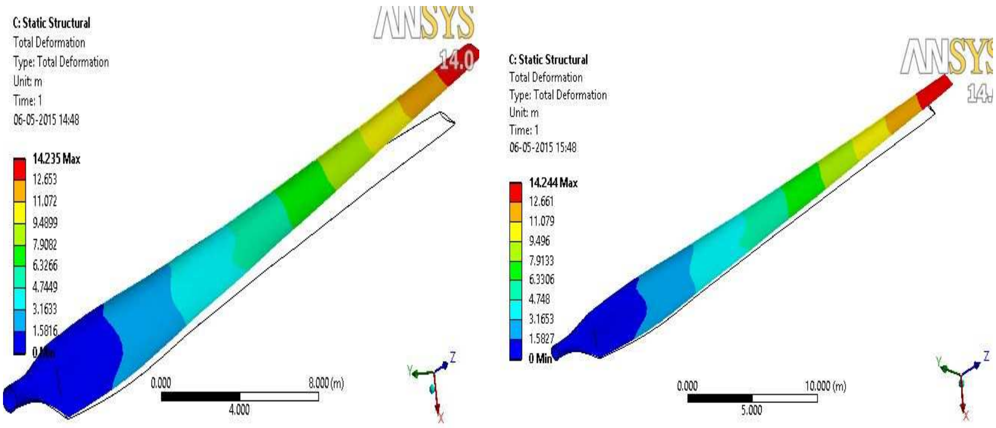


Figure 5.7: Deformation at TSR 5.56 and 7.41 (2-Bladed)

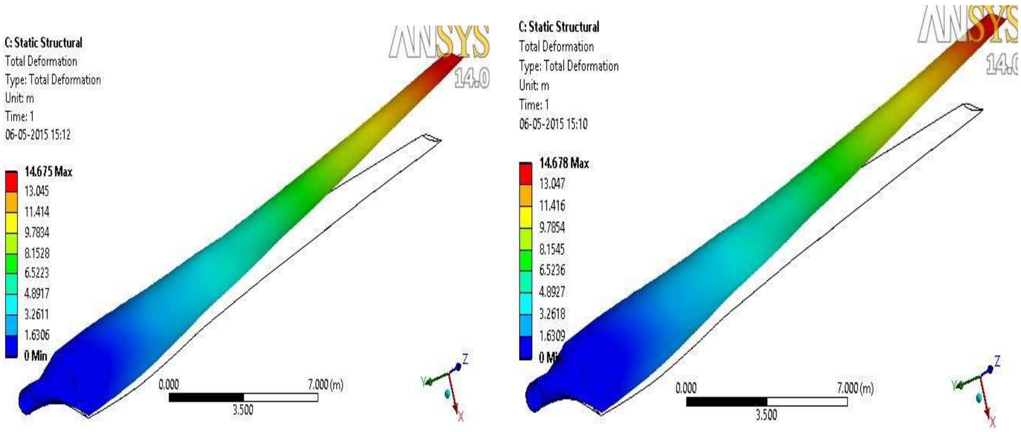


Figure 5.8: Deformation at TSR 1.85 and 3.70(3-Bladed)

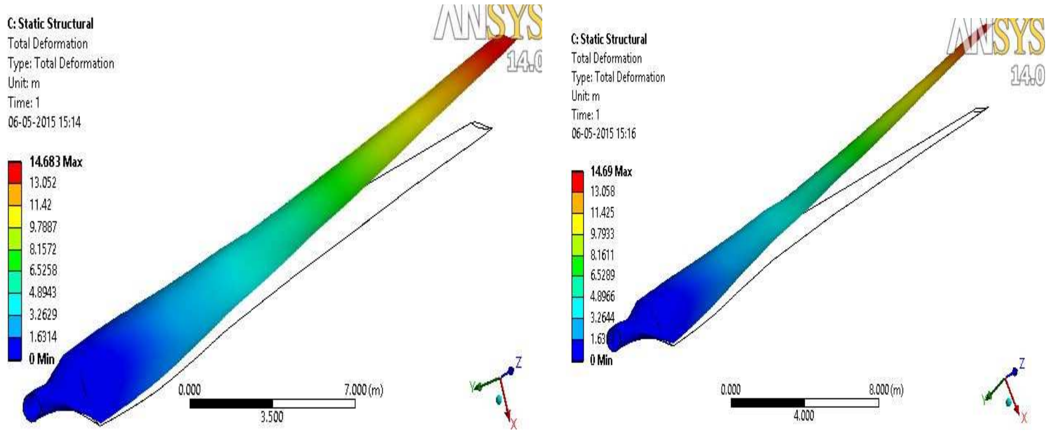


Figure 5.9: Deformation at TSR 5.56 and 7.41 (3-Bladed)

The details of the stress distribution on the blade surface are illustrated below

Table 5.2: Details of Equivalent Strain

Total Deformation (m)			
For Two Bladed Turbine		**For Three Bladed Turbine**	
TSR:1.85	14.223	TSR:1.85	14.675
TSR:3.70	14.228	TSR:3.70	14.678
TSR:5.56	14.235	TSR:5.56	14.683
TSR:7.41	14.244	TSR:7.41	14.690

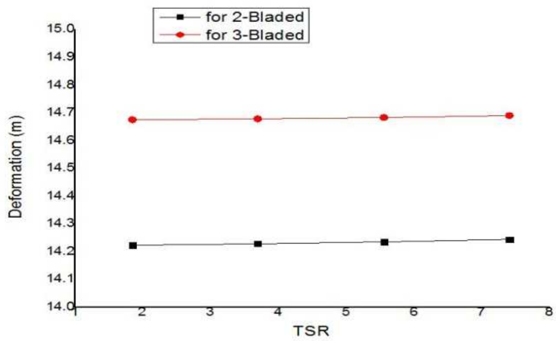


Figure 5.10: Comparison Curve of TSR Vs Deformation

It can be clearly visualized from the above analysis that Tip Speed Ratio does have an effect on the Stress and Deformation developed on the blade surface. Though the effect due to the change in blade no. isn't that high, but it might have a greater effect if we further go on increasing them. However changing the blade material will affect the analysis.

Modal Analysis

The true blade model was taken and was passed through a modal analysis in ANSYS workbench. All the degrees of freedoms of the rotor base have been restricted and a free vibration test has been performed. The mode shapes thus obtained from the analysis are shown below.

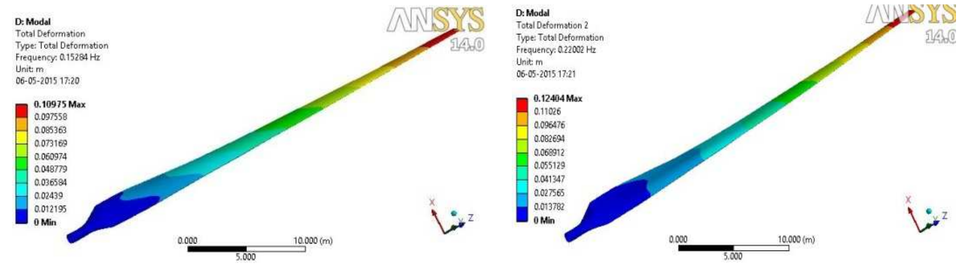


Figure 5.11: 1st and 2nd Mode Shapes

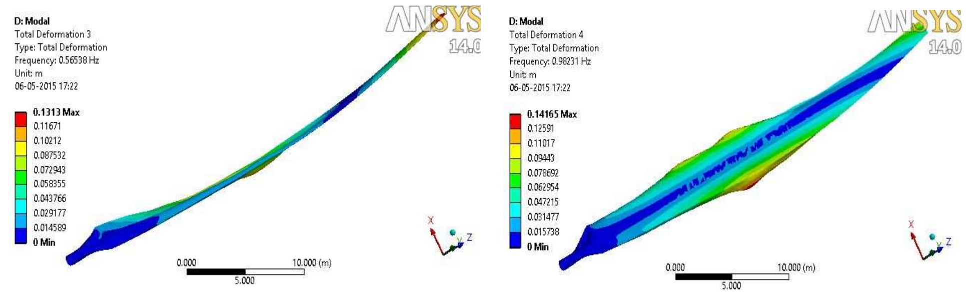


Figure 5.12: 3rd and 4th Mode Shapes

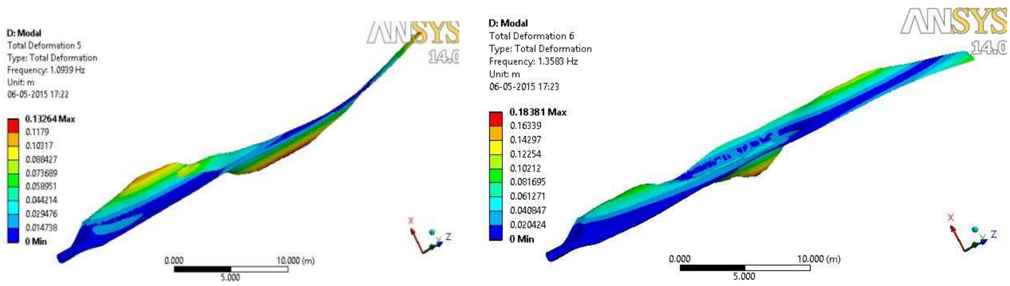


Figure 5.13: 5th and 6th Mode shapes

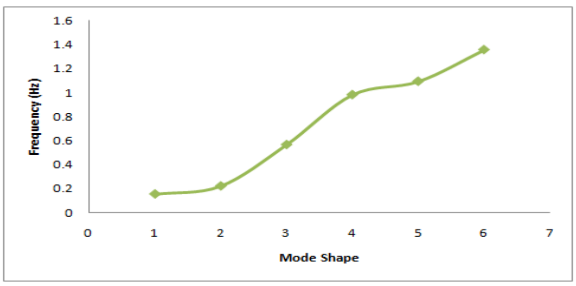


Figure 5.14: Curve for Mode shape Vs Frequency

The curve for variation of frequencies with the change in mode shape is presented in the above figure.

Table 5.3: Comparison Table for Natural Frequency with Refined Mesh

Mode Number	Frequency	Frequency (refined)
1	0.15284	0.17232
2	0.22002	0.24389
3	0.62718	0.61693
4	1.1819	1.16244
5	1.4786	1.4693
6	1.8034	1.7982

In order to check the validity of the analysis, the mesh is further refined The new mesh is having 14901 elements. The mesh after refining shows a good justification for the validation of the model and it was found that the values for the frequencies have approached the limit.

6. CONCLUSIONS

A real world model of a Horizontal wind turbine blade was designed and it’s Structural and natural frequencies are computationally derived in this study. The airfoil selected for the blade design is NREL(National Renewable Energy Labrotory) S-series i.e., S818, S825 and S826. Analysis was conducted using a commercial finite element program ANSYS 14.0 workbench. As per the objective specified, a comparative study has been carried out by changing the rotational speed and the number of blades. The blade was allowed to pass through a fluid flow at a rated 12m/s. After the CFD analysis, the pressure so developed on the blade surface was taken as an input for computing the structural behaviour. Along with the pressure force a varying rotational speed of 5, 10, 15 and 20 revolutions per minute have been taken into account to study the deformation and stress induced in the blade. The material for the blade was taken as E-glass LY556 epoxy resin lamina. It was revealed form the analysis that both the change in TSR and the number of blades do have an effect on the stress developed in the structure. The number of blades taken here are only two and three and it was revealed from the analysis that the effect due to the change is not that high. Besides the modal frequency values showed good agreement with the refinement of the mesh and the geometric model was validated along with the CAE analysis.

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